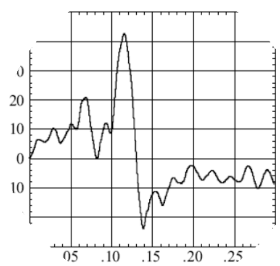
# *Standardization of Analytical and Experimental Methods for Crashworthiness Energy Absorption of Composite Materials (End of Year II)*

*Presented at the JAMS review meeting*
*Wichita, KS*
*July 21-22, 2009*




**Prof. Paolo Feraboli**
*University of Washington*

**Dr. Mostafa Rassaian**
*Boeing Research & Technology*

## Outline

### Motivation

- *Complete lack of standards and accepted practices in testing and analysis of composites under crash conditions*

### Benefits to Aviation

- *Streamline certification process*
- *Increase confidence in analysis methods and therefore level of safety*

### Objective

- *Develop experimental practices and analytical guidelines*

## *Presentation Outline*

- ***Introduction***
- ***Experimental p. 8-18***
  - *Collect and evaluate current test practices*
  - *Develop standard test methods*
- ***Numerical p. 19-33***
  - *Collect and evaluate current modeling practices*
  - *Develop improved modeling techniques*
- ***Future Work p. 34***

## Outline

### Principal Investigator

- *Dr. Paolo Feraboli*

### Boeing Co-PI

- *Dr. Mostafa Rassaian*

### FAA Technical Monitor

- *Allan Abramowitz*

### Other FAA Personnel Involved

- *Curt Davies and Dr. Larry Ilcewicz*

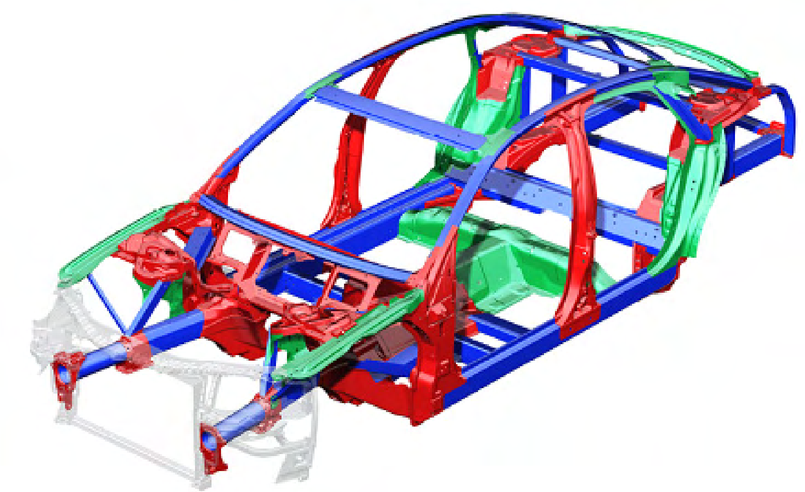
### Industry Participation

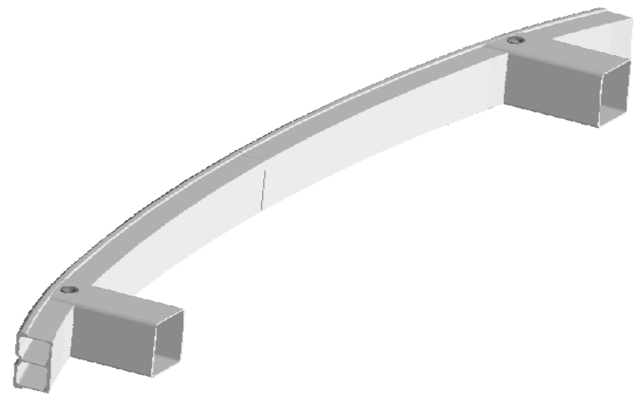
- *CMH-17 Crashworthiness Working Group*
- *Steve Precup and Randy Coggeshall (Boeing)*
- *Leslie Cooke (Toray)*

## *Related Publications*

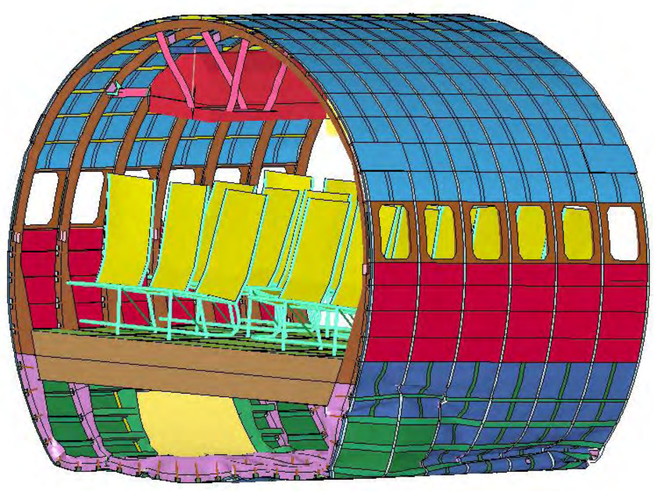
1. *"Development of a corrugated test specimen for composite materials energy absorption"* – Feraboli P. – Journal of Composite Materials - 42/3, 2008, pp. 229-256
2. *"Development of a modified flat plate test and fixture specimen for composite materials crush energy absorption"* – Feraboli P. – Journal of Composite Materials, accepted Jan. 2009.
3. *"Crush energy absorption of composite channel section specimens"* – Feraboli, P., Wade, B., Deleo, F., Rassaian, M. – Composites (Part A), accepted May 2009
4. *"Crushing of composite structures: experiment and simulation",* Deleo, F., Wade, B., Feraboli, P., Rassaian, M., AIAA 50$^{th}$ Structures, Dynamics and Materials Conference, Palm Springs, CA, May 2009, Paper No. 2009-2532-233

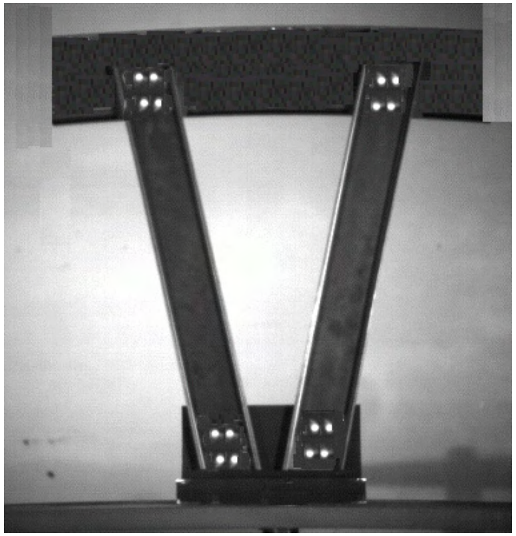
## *Energy absorbers*





***Bumper-rail automotive assembly***

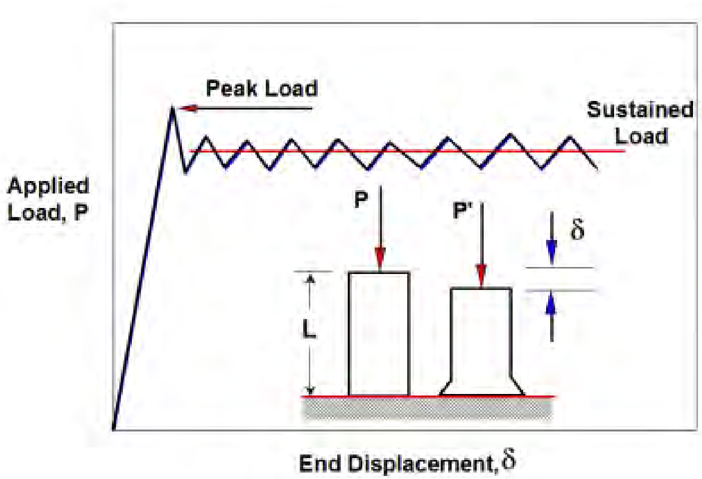




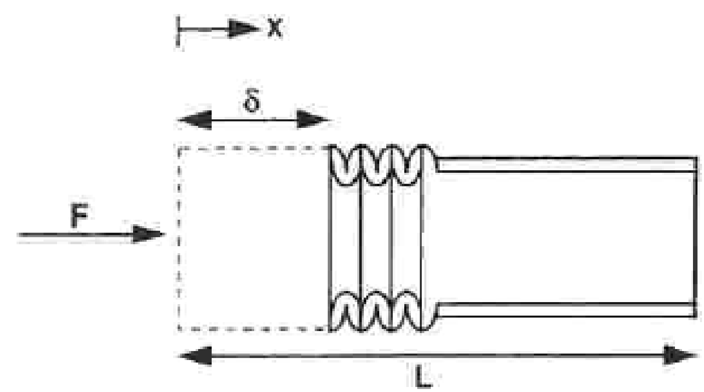
***Stanchion-floor beam aircraft assembly***

## *Measuring Energy Absorption:*

- *Specific Energy Absorption (SEA) is the Absorbed Energy per unit mass of crushed structure,*
- *Absorbed Energy is the total area under the Load-Displacement diagram*




$$SEA = \frac{EA}{\rho \cdot A \cdot \delta} = \frac{\int_0^{\delta} F \cdot dl}{\rho \cdot A \cdot \delta}$$



## *Experiment*

## ***Crashworthiness***

*Experimental Standardization*

- *No existing test standard to determine SEA*
- *No way to screen material systems/ forms/ lay-ups*
- *Material suppliers, OEM’s and regulators need to have common ground*
- *Goal is to develop test standard and design guidelines*

## *Test methods evaluated:*

- *Self-supporting specimens evaluated:*
  - *Three types of sinusoids (corrugated webs)*
  - *Square tube*
  - *Two types of C-channels*
  - *Two types of stiffeners*
- *Specimen requiring support fixture:*
  - *NASA fixture developed in the 1990s was modified to include effect of variable unsupported height (which was its original limitation)*

## *Sinusoidal specimens*

# *Square tube*

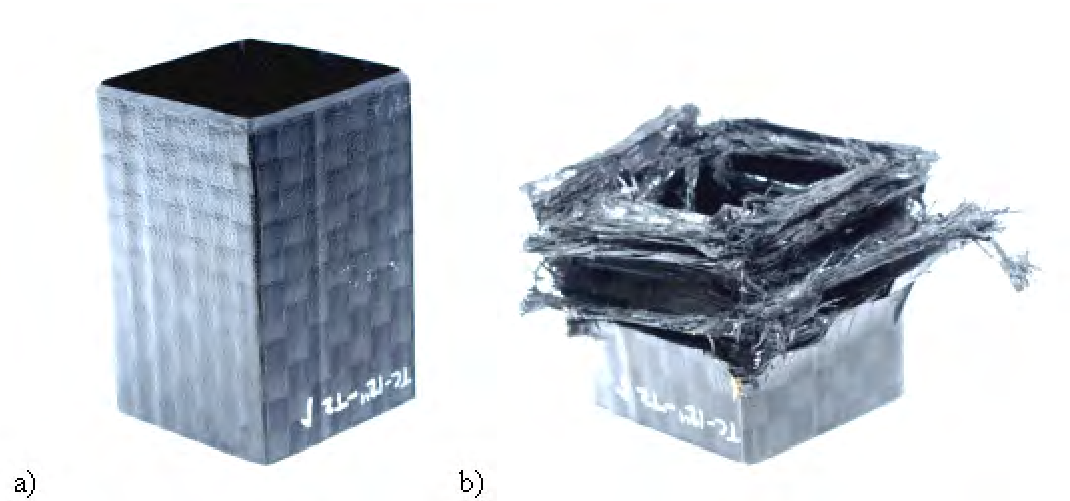
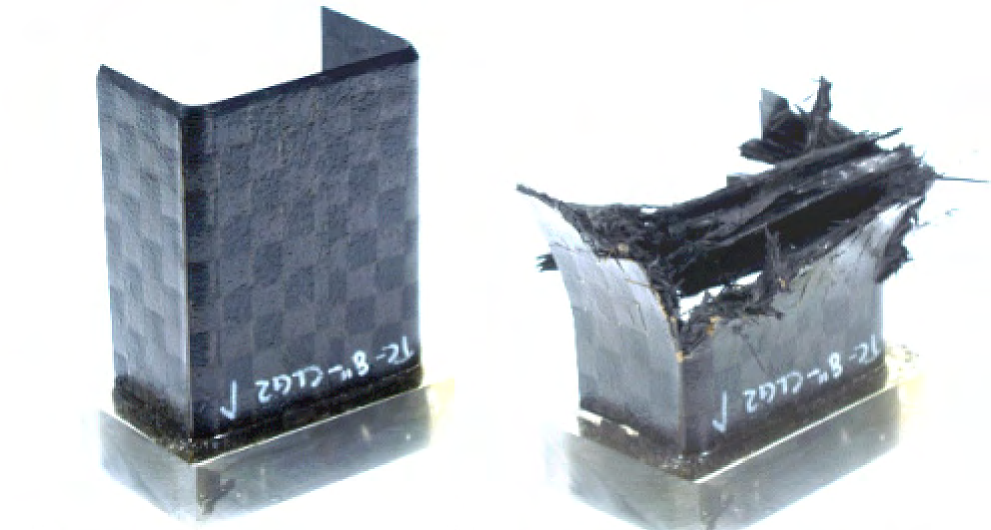


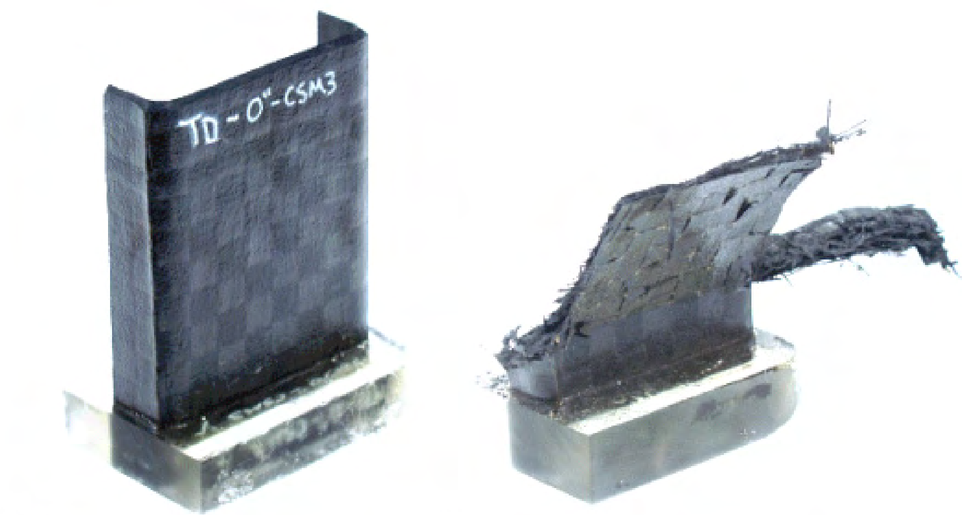

Figure 7 a, b. Square tube, specimen I, before and after crush testing

# *C-channels*



a) b)

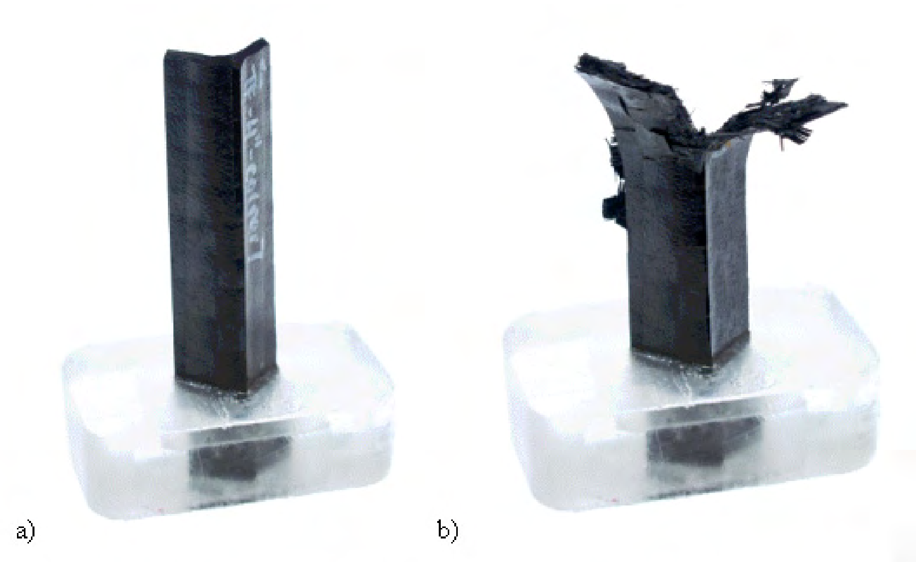
Figure 8 a, b. Large C-channel, specimen II, before and after crush testing.




a) b)

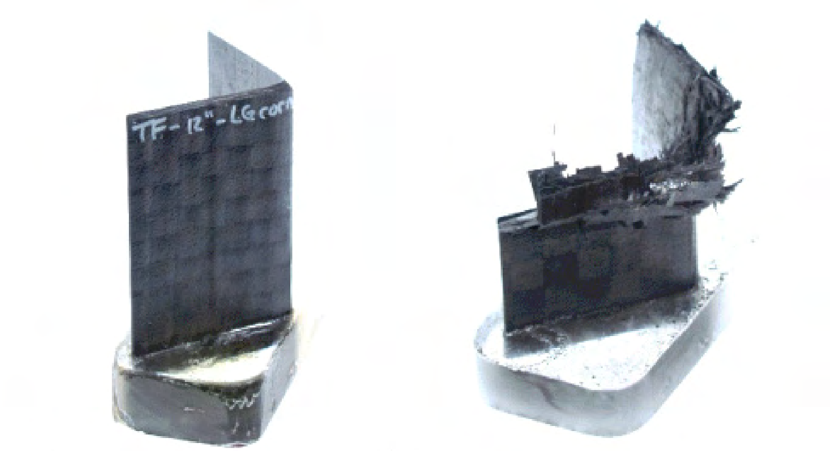
Figure 9 a, b. Small C-channel, specimen III, before and after crush testing.

# *Stiffeners (corners)*



a) b)

Figure 10 a, b. Small corner element, specimen IV, before and after crush testing.



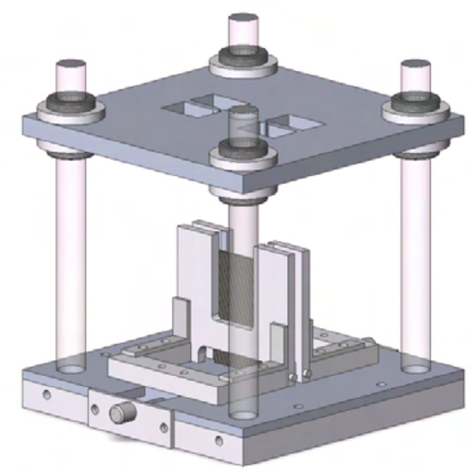
a) b)

Figure 11 a, b. Large corner element, specimen V, before and after crush testing.

# *Flat plate*

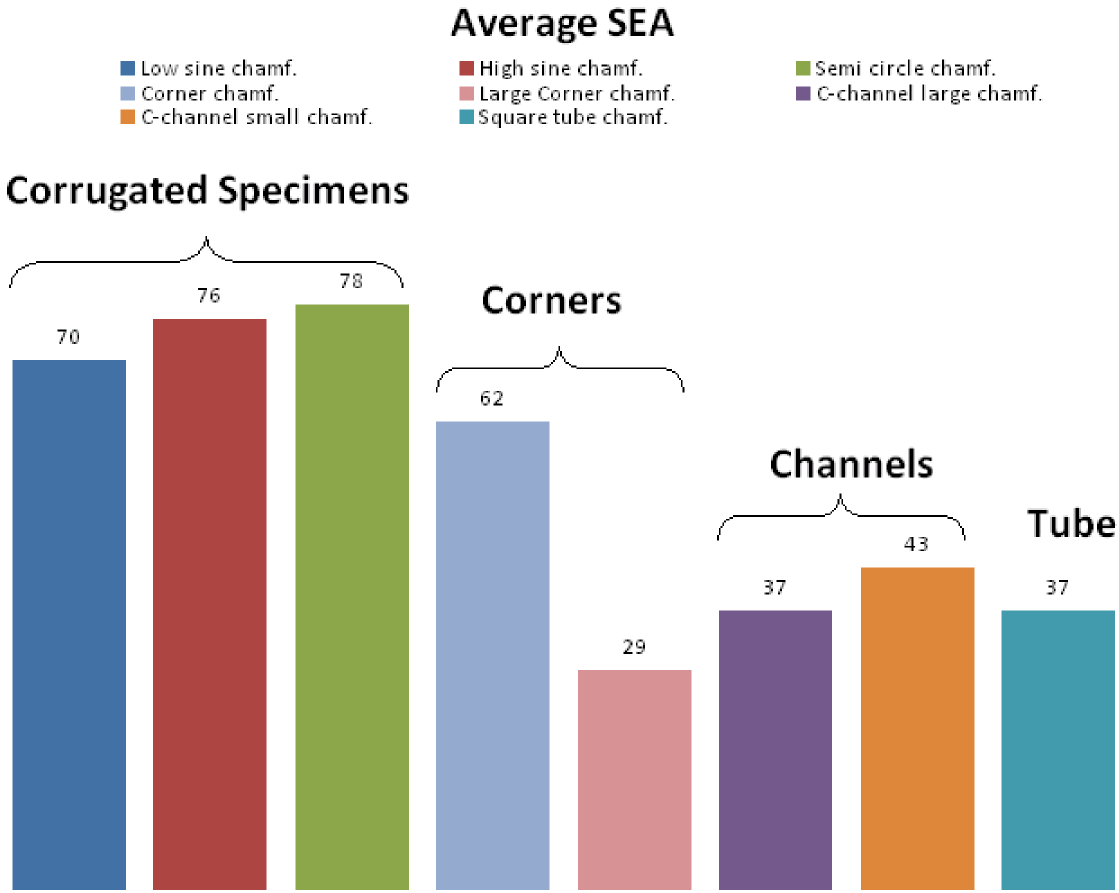
a) b)

Figure 19 a, b. Flat specimen, before crushing showing the saw-tooth trigger (a), and after crushing (b) at 12.5 mm of unsupported height.



## Results

- *Sinusoids have by far highest SEA*
- *Of square tube section elements:*
  - *small corner has greatest SEA*
  - *large corner and square tube the lowest*

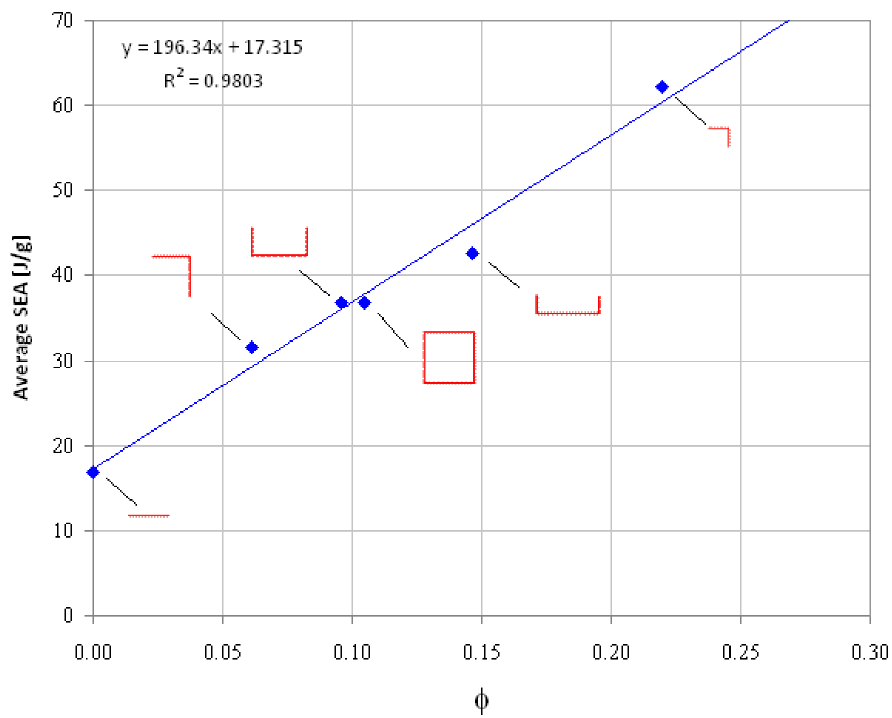


# Curvature effect

variation of SEA with respect to the dimensionless index ϕ, which is an indicator of the degree of curvature of the cross-section, and is given by:

$$\phi = \frac{l}{S_i} = \frac{\pi \cdot r}{2 \cdot S_i} \qquad (7)$$

where $l$ is the arc length, given by the product of the radius r and the angle $\pi/2$, and $S_i$ is length of the cross section influenced by the corner, as defined in eq. (1).



## *Conclusions*

- *SEA not material property but structure's property:*
  - *Highly geometry dependent*
- *Flat segments reduce the amount of energy dissipated*
- *The more curved the specimen, the higher the SEA*
- *Flat plate fixture poses several questions*
  - *Unknown boundary condition effects*
  - *Strong dependence on trigger mechanism*
  - *Variable unsupported height issues*
  - *Difficulties for dynamic testing*
  - *Failure mechanism can differ from other geometries*
- *Two test methods could be developed:*
  - *One for highly curved specimens (such as corner stiffener or sinusoid) for upper bound*
  - *One for flat plate (with related support fixture) for lower bound*

# Crushing of composite structures:

## Experiment and simulation

### *Simulation*

## *Crashworthiness*

- *Numerical standardization*
  - *Current FE modeling strategies are not predictive*
  - *Round Robin initiated involving major FE explicit dynamic codes to characterize material models and modeling strategies*
  - *Goal is to develop guidelines for best analysis practices*

## *Numerical Standardization*

- *Non-linear, dynamic simulation requires explicit FEA codes*
- *Common commercial codes used in this field are:*
  - *LS-DYNA (LSTC)*
  - *ABAQUS Explicit (SIMULIA)*
  - *PAM-CRASH (ESI)*
  - *RADIOSS (ALTAIR)*
  - *NASTRAN-DYTRAN (MSC)*
- *Each code is unique for:*
  - *Material models*
    - *Failure criteria implementation*
    - *Strength and stiffness degradation strategies*
  - *Other code parameters*
    - *contact definition*
    - *damping, time steps, etc…*

## *Modelling strategies with LS-DYNA*

- *LS-DYNA considered benchmark for crash analysis*
- *Composite constitutive models are continuum mechanics models - treat as orthotropic linear elastic materials within a failure surface*
- *Failure criterion varies*
- *Beyond failure, elastic properties follow degradation laws:*
  - *progressive failure models (PFM)*
  - *continuum damage mechanics (CDM) models.*

Table IV. Summary of composite material models available in the commercial explicit FE code LS-DYNA.

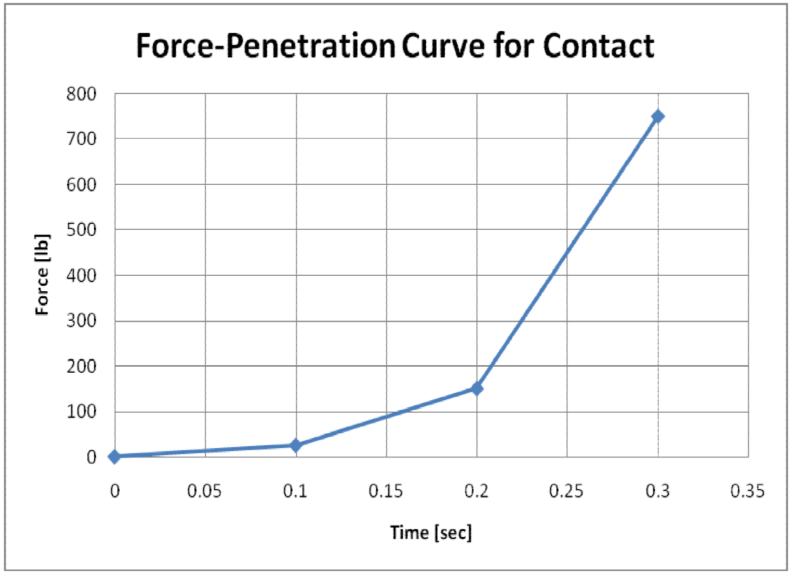
| MAT | Title | Brick | Shell | T-shell | Degradation Law |
|---|---|---|---|---|---|
| 22 | Composite Damage | y | y | y | Progressive failure |
| 54/55 | Enhanced Composite damage | | y | | Progressive failure |
| 58 | Laminated Composite Fabric | | y | | Damage Mechanics |
| 59 | Composite Failure | y | y | | Progressive failure |
| 161 | Composite MSC | y | | | Damage Mechanics |
| 162 | Composite MSC | y | | | Damage Mechanics |

## *MAT54 characteristics*

- *Material failure based on* ***Chang/Chang criterion (Strength based).***
- *Each time step, plies of the MAT54 elements are checked and modified using "progressive damage".*
- *Once all plies have failed element is deleted*
- ***Failure can also occur if these parameters are exceeded:***
- ***DFAILM****. Maximum strain for matrix in tension or compression.*
- ***DFAILS****. Maximum shear strain (active only if DFAILT > 0).*
- ***DFAILT****. Maximum strain for fiber tension.*
- ***DFAILC****. Maximum strain for fiber compression.*
- ***TFAIL****. Time step criteria for element deletion*

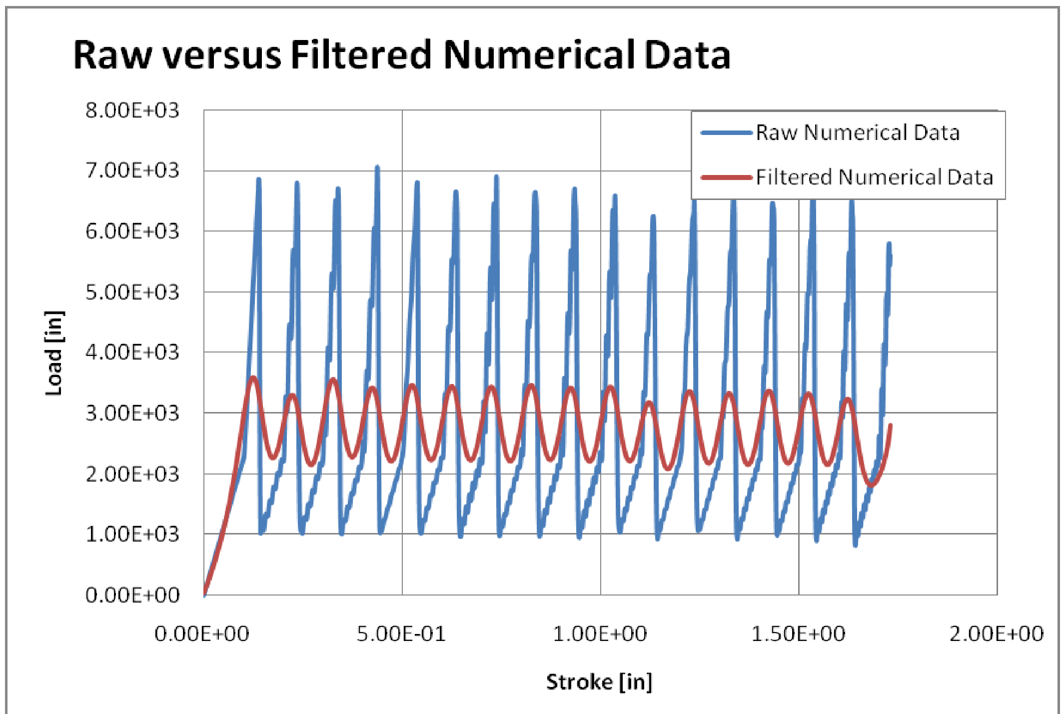
## *MAT54 additional parameters*

- ***SOFT***. *Softening reduction factor for material strength in crash front elements (varies between 0 and 1, default = 1.0).*
- ***Force-penetration** curve: characteristic of the contact definition*
- ***Contact formulation***
- *These parameters need to be calibrated using trial-and-error.*



## *LS-DYNA model characteristics*

- *Filtering with SAE 600Hz.*
- *Dell Precision PWS 380 Dual Core*
- *Pentium D CPU 3.2 GHz, 2 Gb RAM*
- *Simulations take 47000 – 52000 cycles, approximately 1400 sec, 23 mins.*



# Example: crushing of square tube

- *Trial and error procedure to find the “right” SOFT parameter that matches the experiment*
- *Vary only SOFT parameter*

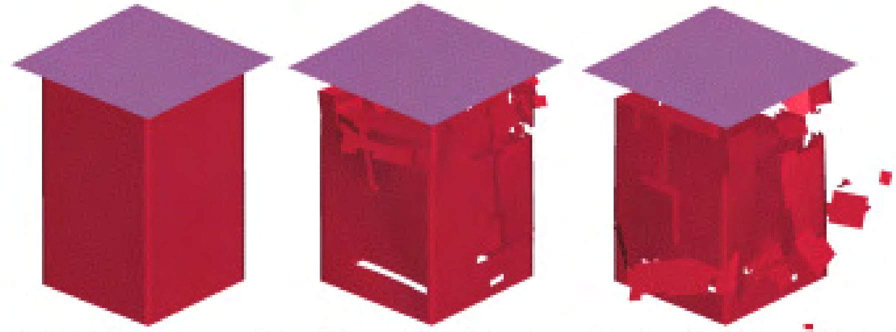


Figure 12. Example of an unstable crushing of the tubular shape with SOFT=0.64 Buckling starts after 2.446millsec at a displacement of 0.3669 inches.

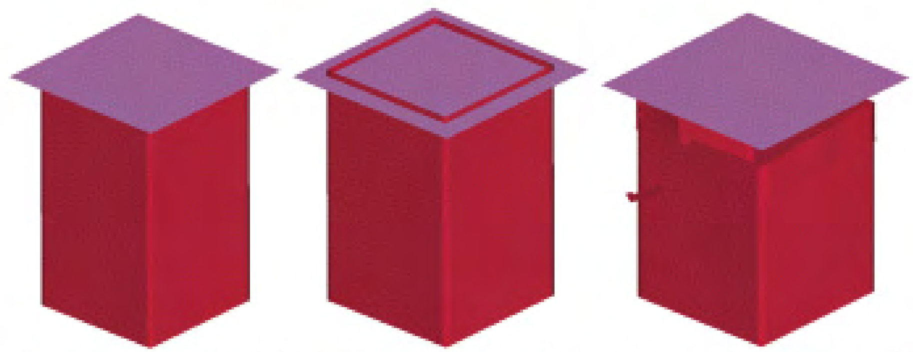


Figure 13. Example of an unstable crushing of the tubular shape with SOFT=0.3. Buckling starts after 3.728millsec at a displacement of 0.5592 inches.

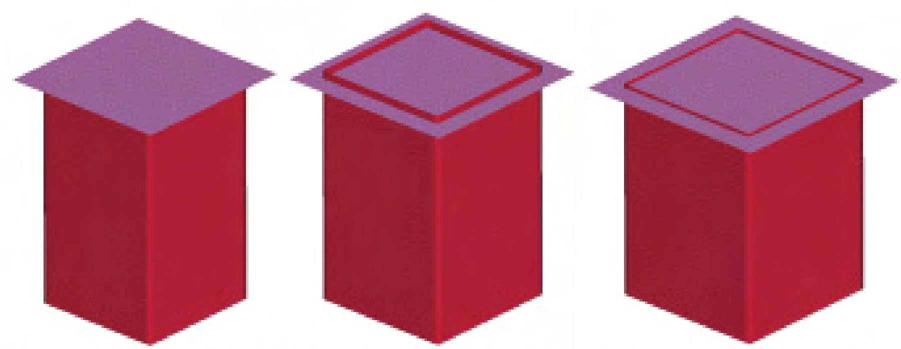
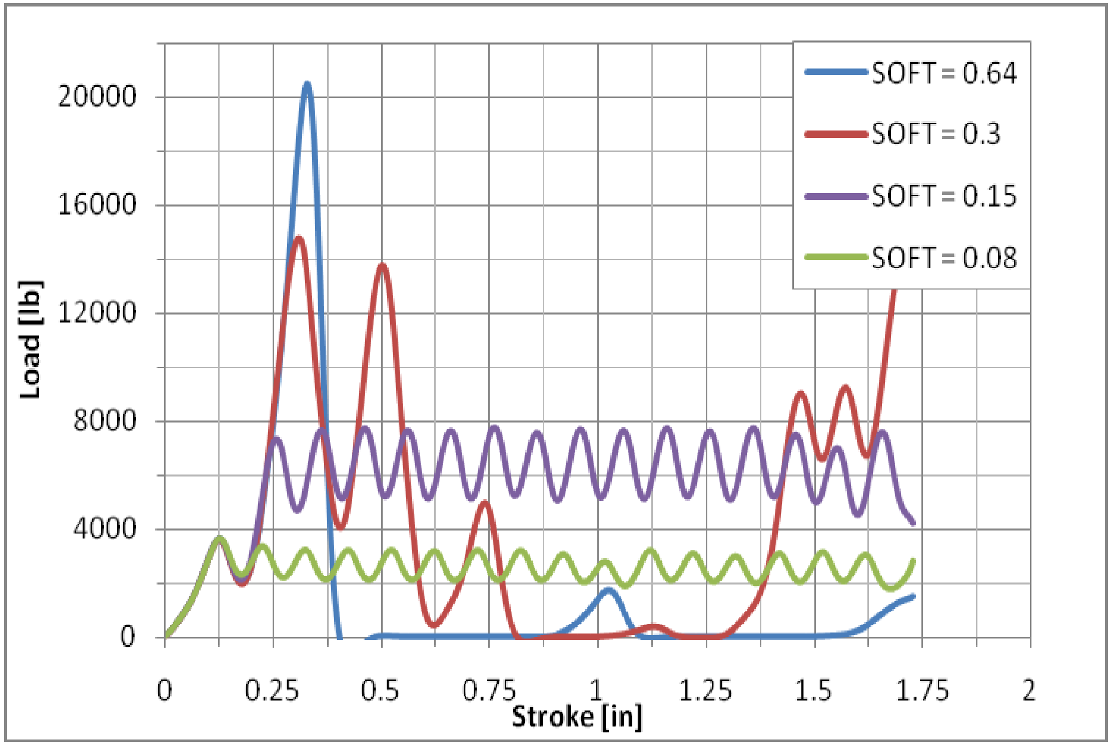


Figure 14. Example of a stable crushing of the tubular shape with SOFT=0.08. No buckling.

## *Example: crushing of square tube*

- *Trial and error procedure to find the "right" SOFT parameter that matches the experiment*
- *Vary only SOFT parameter – every other property remains the same*



# *All geometries*

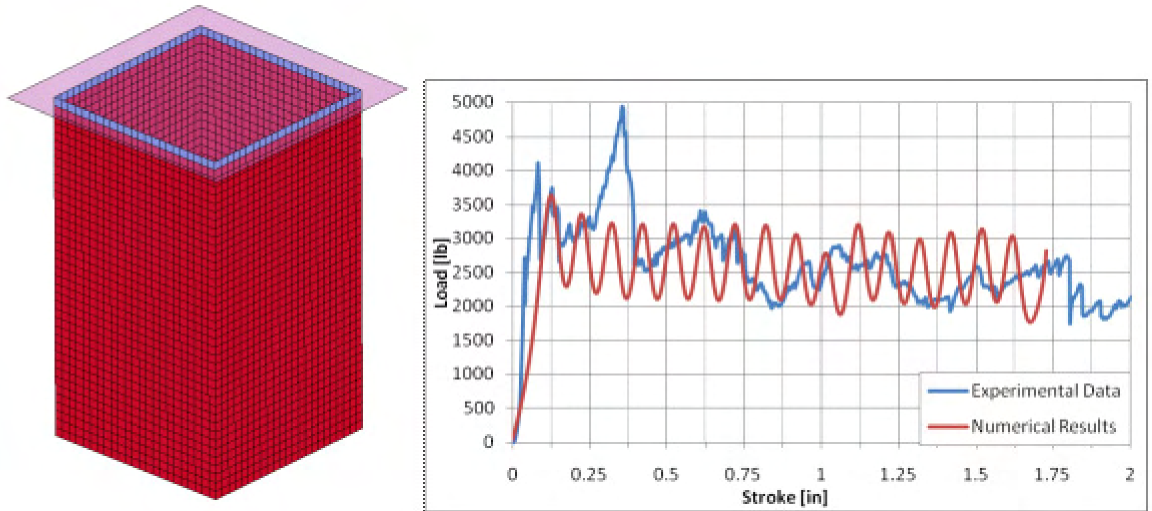



Figure 16. Model geometry and optimal Load-Displacement curve for the square tube specimen

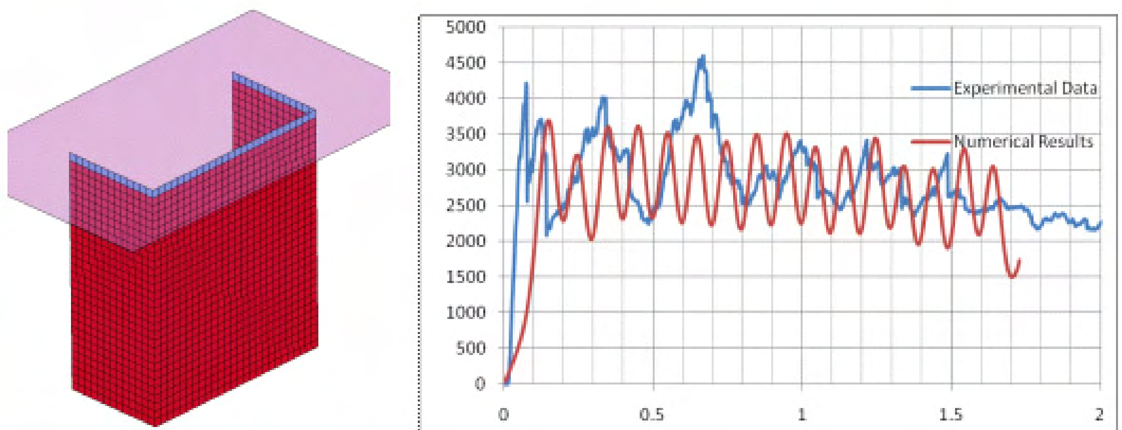
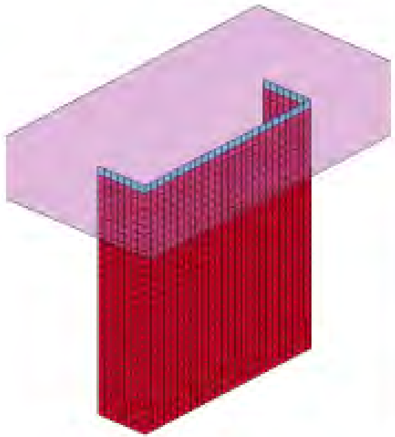



Figure 17. Model geometry and optimal Load-Displacement curve for the large C-Channel specimen.

# *All geometries*



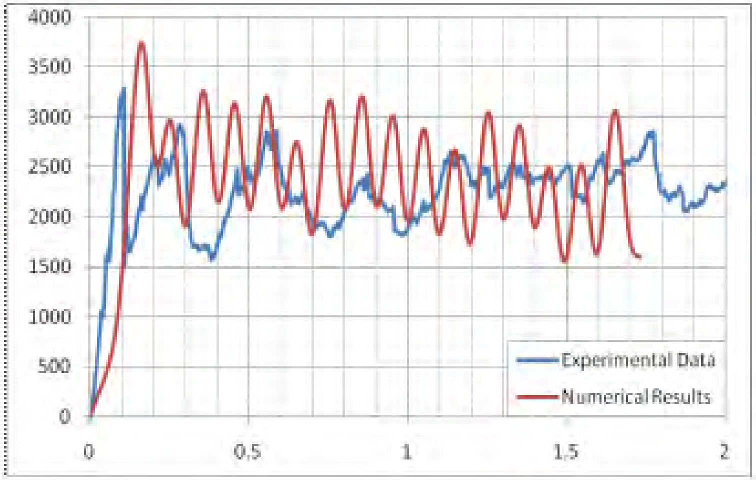
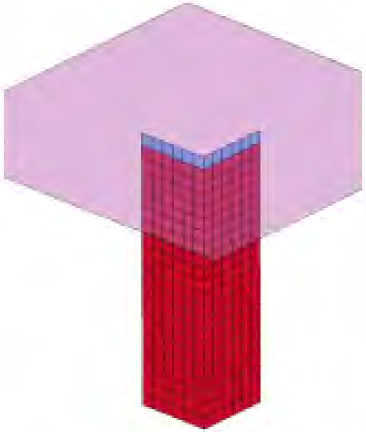



Figure 18. Model geometry and optimal Load-Displacement curve for the small C-Channel specimen.



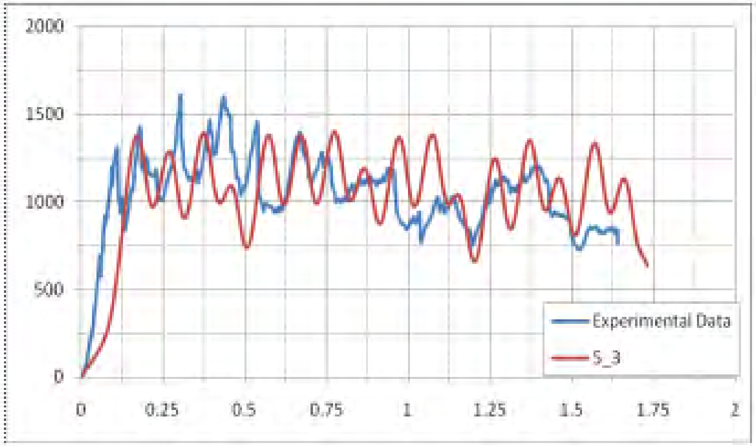



Figure 19. Model geometry and optimal Load-Displacement curve for the small corner specimen

## *All geometries*

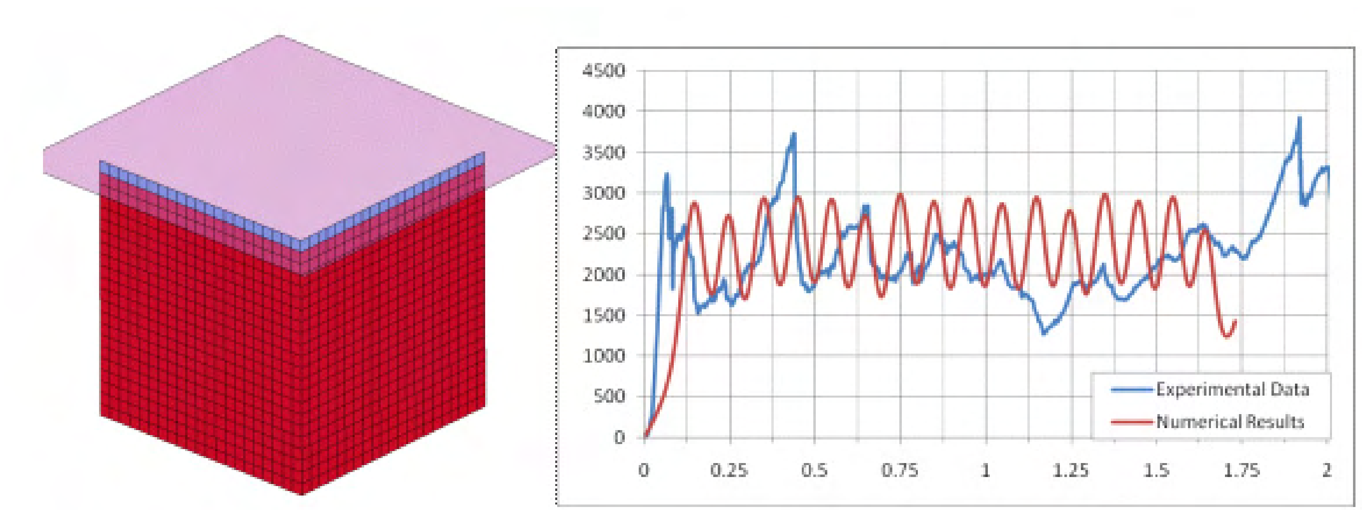



Figure 20. Model geometry and optimal Load-Displacement curve for the large Corner specimen

## ***Observations***

- *For all geometries it is possible to find a suitable value of the SOFT parameter by trial and error*
- *Each geometry is characterized by a specific value of SOFT that matches the experimental data, while keeping all other parameters unchanged*
- *The same input deck cannot be used to predict all geometries "as-is"*
- *Thus the building block approach cannot be used "as-is" to scale from a coupon test to any other geometry*
- *The SOFT parameter needs to change for each geometry, it is a necessary and sufficient condition to lead to stable crushing*
- *Used to reduce the strength of the row of elements immediately following that under crushing so that crushing occurs rather instability or other failures away from the crush front*
- *SOFT parameter is a tweaking parameter….*

## *Observations*

- *However, SOFT parameter appears to have a physical meaning*
- *There appears to be a linear correlation between stability, curvature and SOFT parameter*

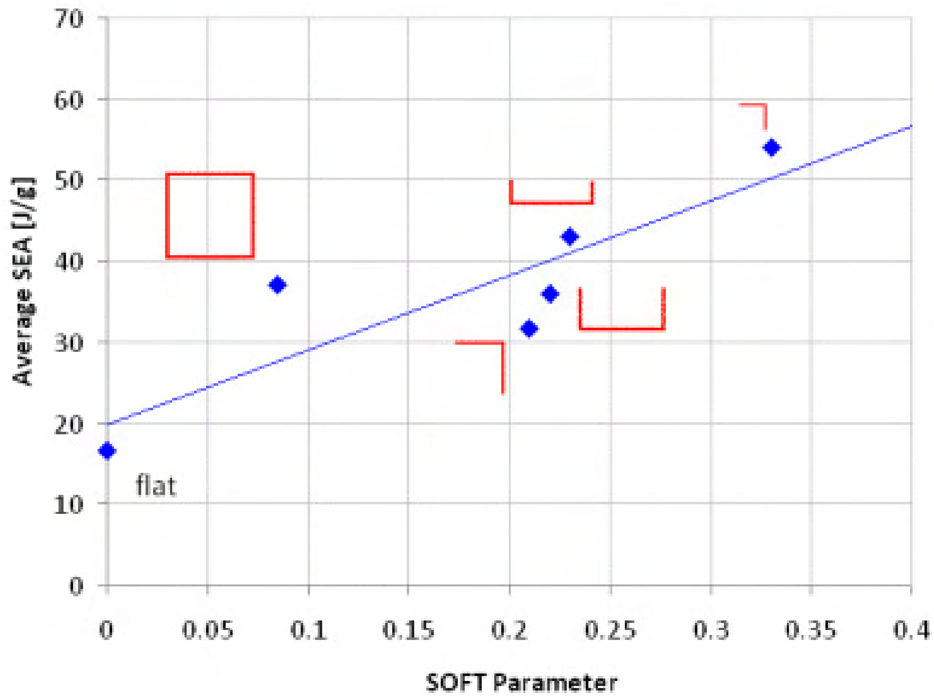
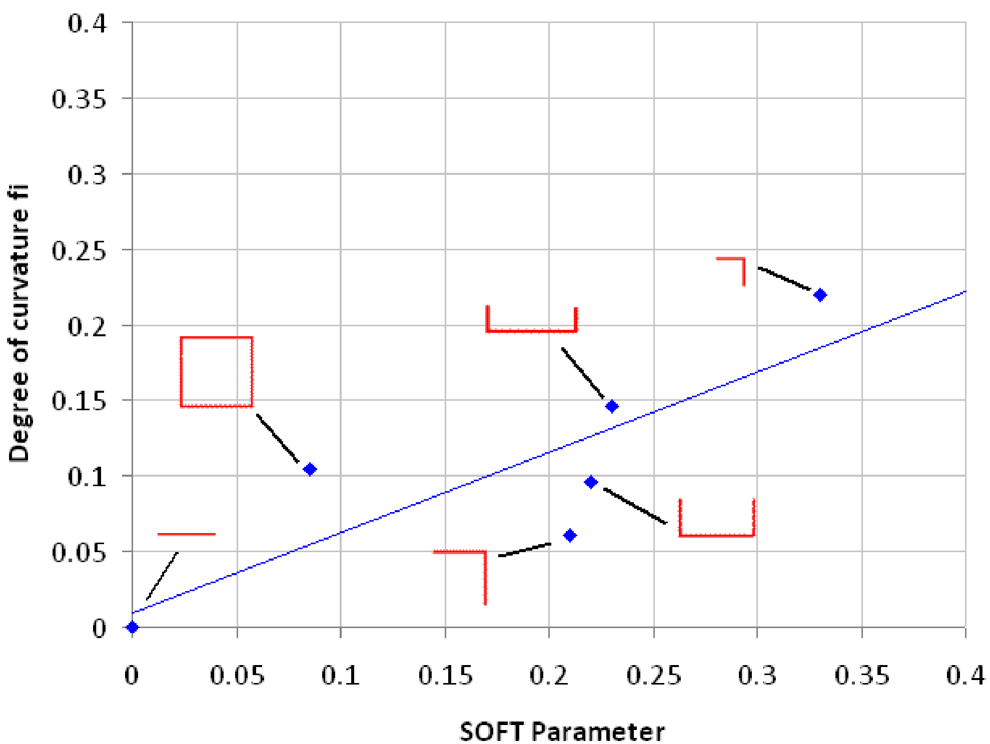



Figure 21. Linear relation between the SEA and the SOFT parameter

## *Conclusions*

- *SOFT parameter appears to be an indicator of how large the damage zone ahead of the crush front is, hence what percentage of strength is available ahead of the crush front*
- *The more stable the section is, the more contained the damage is ahead of the crush front and hence the less the strength reduction of the row that follows needs to be*



## *Conclusions*

- *Current crash simulation tools are all but predictive*
- *Use of the Building Block Approach to certify by analysis is possible by highly complex*
- *Modeling strategies require the use of tweaking parameters that cannot be measured experimentally, need to be calibrated by trial and error, and may have no physical significance*
- *The need to produce numerical guidelines is very important to prevent users from running in gross mistakes associated with the selection of these parameters.*

## *Planned Work for Year III*

- *Significant reduction in FAA funding will impose delay in some of planned activities.*
- *Original plan to perform dynamic crushing of specimens and to build a full-scale subfloor assembly for crash testing*
- *Postpone manufacturing of new test specimens for dynamic crushing and subfloor assembly to Year IV*
- *Shift focus to simulation: small specimens as well as full-scale subassembly*
- *Focus on completing detailed evaluation of MAT 54 in LS-DYNA and associated publications*
- *Initiate study of same structures using MAT 58 in LS-DYNA*
- *Summarize results in journal publications and technical report*